Compressive creep behavior of corrugating components affected by humid environment

John M. Considine, Denise L. Stoker, Theodore L. Laufenberg, and James W. Evans

ABSTRACT: *This study examined how conditions of cyclic humidity over a range of commercially available processes and materials affected compressive creep properties of containerboard components. Because of the variability and small number of replications, statistical differences between materials were small. Compressive strength, failure strain, stiffness, or energy absorption did not predict creep performance. Hygroexpansive strain does not provide adequate prediction of creep performance. The paper examines a test method to evaluate behavior of corrugated containers in varying moisture environments.*

KEYWORDS: *Compression strength, container boards, corrugated boxes, creep tests, humidity, hygroexpansivity.*

In environments of high humidity, corrugated containers typically have between 10% and 20% of their compressive strength at 50% RH. Typical design safety factors throughout the containerboard industry range from 7 to 20, e.g., produce containers. With an increased understanding of how corrugated container components behave in uncontrolled environments, it is possible to reduce wood fiber use.

Many companies have developed high-performance (HP) linerboard as a high-strength alternative to conventional linerboard. Although HP linerboard may exhibit high strength in TAPPI test conditions, one never knows if the strength benefit will occur through the entire spectrum of moisture exposure in a particular environment.

Recent alternatives to Item 222 and Rule 41, which are new rail and trucking regulations, are changing the manner of characterization of the performance of corrugated components. Substituting the edgewise crush test (ECT) for burst strength improves the prediction of the useful life of a container in conditions of 50% RH. Further refinement of the certification may be necessary to provide customers with behavior predictions in other environments.

These conditions demonstrate the dynamic nature of the corrugated container industry. They examine the questions and concerns that a properly designed test method or procedure must address. Such a test or series of tests, i.e., procedure, would examine the behavior of corrugated components under different conditions of specified relative humidity. With increased knowledge of corrugated component behavior, package engineers could confidently reduce design safety factors in corrugated containers. It would be possible to understand new products, treatments, and machine variables in a manner that could affect long-term container behavior. In addition, new regulations will most likely incorporate increased knowledge of container behavior in the end-use environment.

This study provides the preliminary work for the development of a test method or procedure that will evaluate the behavior of corrugated containers in varying moisture environments.

Literature review

Mechano-sorption is the interaction between load and moisture-sorption behavior that one cannot predict by the superposition of these behaviors.

Considine is research general engineer, Stoker Is general engineer, Laufenberg is supervisory research general engineer, and Evans is supervisory mathematical statistician at USDA Forest Service, Forest Products Laboratory, One Gifford Pinchot Dr., Madison, WI 53705.

This effect occurs in all wood and wood products. Reduced duration of load in changing moisture environments provides the most frequent recognition of this behavior.

Byrd (*1,2*) examined the tensile and compressive creep behavior of paperboard in environments of cyclic humidity and compared these results to creep tests in environments of constant humidity. At equal creep loads, he showed that the specimens in environments of cyclic humidity had higher creep rates and more frequent failures than those in environments of constant humidity. Byrd also performed tensile creep tests on single fibers. Results showed that the fibril angle decreased in environments of constant relative humidity but increased in environments of cyclic relative humidity.

Later, Byrd and Koning (*3*) examined the compressive creep behavior of ECT specimens. In that work, they showed that recycled paperboard and high-yield paperboard had greater deformation than did virgin, low-yield paperboard. The differences between these paperboards were not evident during creep at constant relative humidity-only during cyclic relative humidity.

In 1984, Byrd (*4,5*) examined the compressive creep behavior of paperboard. He further validated previous results by showing that high-yield and recycled paperboard performed more poorly than did virgin, low-yield paperboard. He also showed that the rate of creep related to the moisture uptake of the paperboard. Furthermore, Byrd showed that the deformation of the components was not as large as that of the ECT specimens made with the same material. He proposed a mechanism of creep under cyclic humidity based on his measurements of moisture content during creep tests. His experiments found that moisture content continually increases during creep tests.

Soremark and Fellers (*6*) examined the bending behavior of corrugated specimens in environments of constant and cyclic humidity. They proposed an additional mechanism that contributes to the large deformations in environments of cyclic humidity. After they accounted for deformation, they found that the amount of hygroexpansion depended on whether the specimen was in compression or tension loading. They called this phenomenon stress-induced hygroexpansion. Compression increases hygroexpansion, and tension reduces hygroexpansion.

Leake (*7*) examined the behavior of boxes loaded in top-to-bottom compression and subjected to environments of constant and cyclic humidity. He found that ECT results at 50% and 90% RH could not predict the box behavior in environments of cyclic relative humidity. This study also demonstrated the important contribution of the corrugating medium in box behavior.

Several researchers have tried to determine the mechanisms of accelerated creep of paperboard in environments of cyclic humidity. Back et al. (*8, 9*) measured the transient mechanical behavior of paperboard during tension while sorbing moisture. They compared their results with researchers working on wool and other natural fibers. They concluded that the rate of moisture sorption governed the amount of transient behavior. As a result of transient behavior, stiffness and strength are a function of moisture content and the moisture content gradient. In other words, at equilibrium conditions for a given material, stiffness and strength are solely functions of moisture content. During moisture sorption, however, the rate of moisture change also affects stiffness and strength.

Using ultrasonic techniques, Berger and Habeger (*10*) did not measure transient behavior. Rather they measured significant temperature changes of the specimens during moisture sorption and corrected for these in their measurements. They suggested that the transient phenomena could be a finite strain event not detectable by their ultrasonic techniques. previous work indicated that ultrasonic measurement techniques did not measure as large a property difference as did finite strain measurement techniques because of moisture content differences.

Gunderson (*11*) and Gunderson and Tobey (*12*) developed an apparatus to measure one part of mechano-sorptive behavior-the moisture changes resulting from load. They measured moisture loss during compressive loading and moisture gain during tensile loading. The amount of moisture change was very small, however, and probably did not appreciably change the mechanical properties of the material. An interesting aspect of this work was the frequency independence of the mechano-sorptive creep. The creep was independent of the frequency of moisture change and depended only on the number of moisture cycles. This assumes all the moisture cycles were between the same levels of relative humidity.

Considine *et al.* (*13*) measured the compressive creep behavior of paperboard in an environment of cyclic humidity. In that experiment, they observed a reduction of paperboard stiffness directly related to the amount of creep. They also measured compressive creep strains several times larger than those measured during short-term compressive strength tests at constant relative humidity.

From this selective literature review, it is obvious that paperboard experiences rather unpredictable changes in properties during moisture sorption. Static tests of relative humidity are not sufficient to predict this behavior. At this time, we are not aware of a comprehensive model describing mechano-sorptive behavior including the behavior of paperboard during compressive creep in an environment of cyclic humidity.

Experimental design

Objective

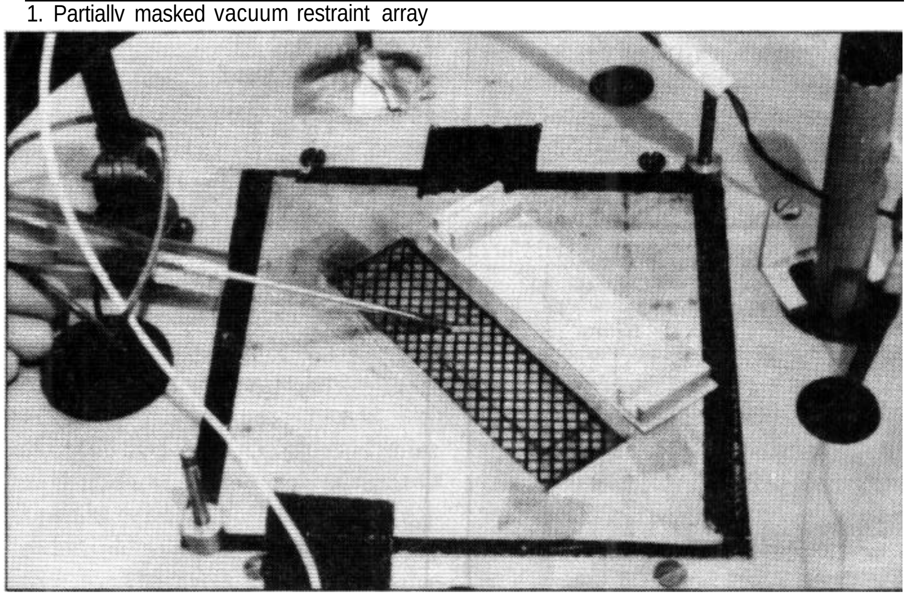
The objective of this study was to determine how conditions of cyclic humidity across a range of commercially available processes and materials af-

I. Papers used for component testing

Class	Region	Compressive index	Process	Paper codes
Linerboard (69 lb)	South	High		HS
		Low		LS
	West	High		HW
		Low		LW
Corrugating medium (26 lb)			NSSC*	NSSC
			Green liquor	GL
			Recycled	R

*Neutral sulfite semichemical

1. Partiallv masked vacuum restraint array



fect the compressive creep properties of containerboard components.

Materials tested

The study involved two groups of materials for testing: 26 lb/1000 ft^2 (127 g/m^2) corrugating medium and 69 lb/1000 ft^2 (337 g/m^2) linerboard. We designated these as 26 lb and 69 lb, respectively. **Table I** indicates the codes for each of the papers in the testing.

Each paper type received by our organization underwent preliminary compression testing using our own procedure to obtain a compression index. For this study, the definition of compression index was the geometric mean of the machine direction (MD) and cross direction (CD) strengths. Because the MD strength values are greater than the CD strength values, this compression index weighs the MD strength more than the CD strength. Although we used the compression index in selecting linerboard, we also considered regional sources, processing, and basis weight.

Equipment

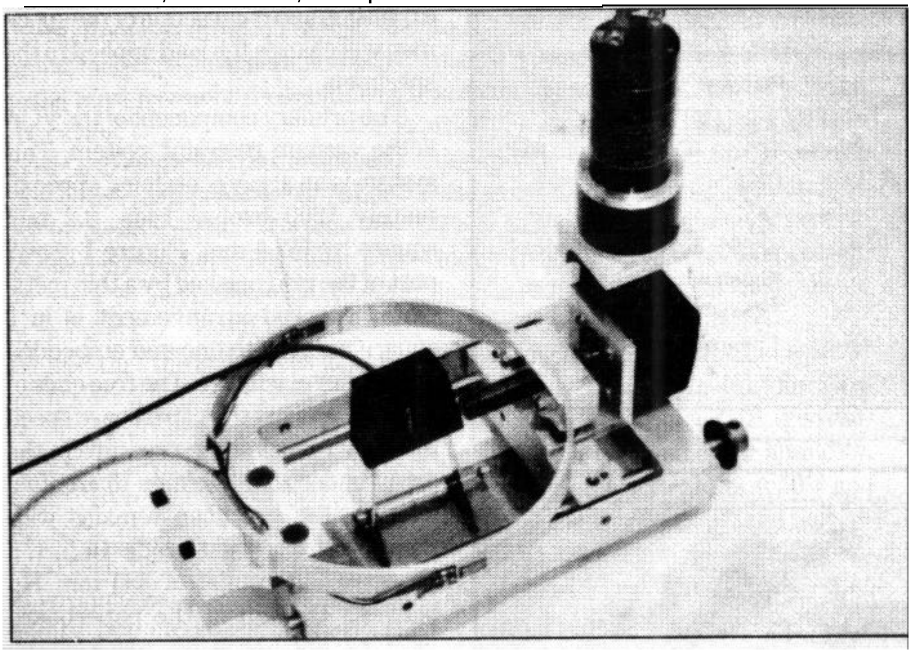
We used a vacuum compression apparatus (VCA) to conduct all tests other than the preliminary tests (*14*). The VCA consists of a load frame and a vacuum restraint system enclosed in an environmentally controlled chamber. With closed-loop, load-rate control, a computer can command the load frame to maintain a specified load regardless of strain magnitude. Load-rate control is important for testing of cyclic humidity because the hygroexpansion and contraction of the specimen will change the load applied to the specimen.

The primary component of the VCA is the vacuum restraint system. This system is an array containing approximately 1200 bronze rods, 3.2 mm square by 152.4 mm. **Figure 1** shows part of the grid masked by a thin metal plate. The rod arrangement is in a square array with one end embedded in a rubber elastomer. The free ends of the rods support the paperboard specimen. By reducing the pressure in the array under the specimen to create a vacuum, the specimen remains with the tops of the bronze rods. In fact, a pressure differential of 380 mm Hg between the top of the paperboard specimen and the bottom is sufficient to prevent the specimen from buckling while loaded in edgewise compression.

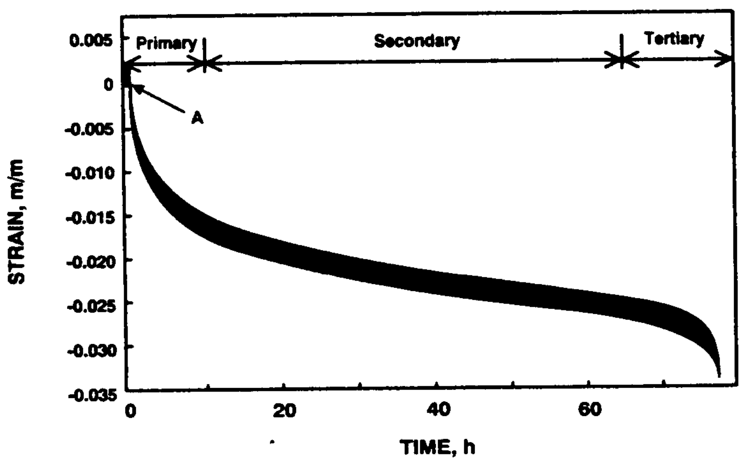
A small test chamber encloses the vacuum restraint system. A pressure differential creates air movement through and around the specimen. By changing the moisture content of the air within the test chamber, it is possible to test the specimen under several conditions of relative humidity. The VCA is able to control the test chamber relative humidity to within 1% under conditions of specified constant or changing relative humidity. The control system for relative humidity is able to change from 30% to 90% RH in approximately 1 min. Because the system pulls the air through and around the specimen, the specimen responds quickly to changes in relative humidity. Most papers and paperboards reach dimensional stability within 10 min of a change from 30% to 90% relative humidity.

The load fixture engages the specimen by means of tabs glued to the specimen. Through these tabs, the load fixture can measure and apply load. A load cell in the fixture measures load. An extensometer riding on the specimen measures deformation. **Figure 2** shows a specimen in the load fixture and the extensometer.

2. Load fixture, extensometer, and specimen



3. Typical compressive creep test



II. Compression test matrix

Test Variation	No.
Creep	
Paper types:	7
3 at 26 lb	
4 at 69 lb	
Environments:	4
50% RH at high load	
90% RH at high load	
Cyclic at high load	
Cyclic at low load	
Directions:	2
MD	
CD	
Replications:	4
Total (7 by 4 by 2 by 4)	226
Compression	
Paper types:	7
3 at 26 lb	
4 at 69 lb	
Environments:	2
50% RH	
90% RH	
Directions:	2
MD	
CD	
Replications:	4
Total (7 by 2 by 2 by 4)	112

Test procedures

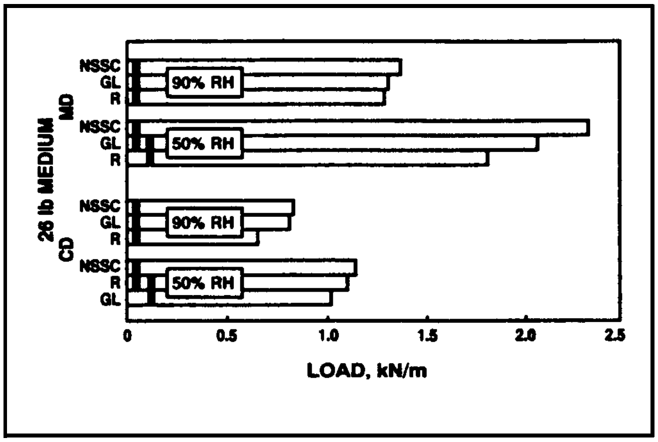
Table II shows the test matrix for the experiment. There were a minimum of four creep tests per test condition. The results show high and low creep loads because the creep loads were a percentage of the compressive strength. The percentages were different for the corrugating medium and linerboard.

We conducted the cyclic creep tests for relative humidity with sinusoidal cycles for humidity that had a 70% RH mean, a 20% RH amplitude, and a 10-min cycle. The relative humidity cycled between 50% and 90%. We conducted the creep tests at constant relative humidity at both 50% and 90%. Temperature was ambient-generally 78°F (26°C) for all tests.

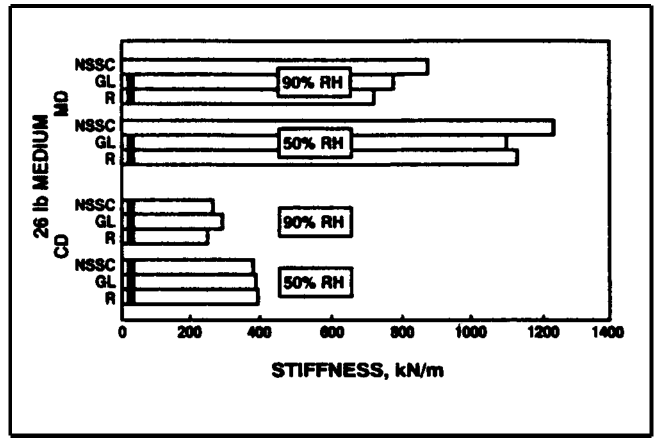
We determined load levels on the basis of compressive strength measured in the preliminary compression tests. The desired length of the creep test determined the percentage of compressive creep load used. For the corrugating medium, we used 25% and 35% of the compressive strength for the 14 h and 5 h tests, respectively. Tests terminated at 14 h for the low-load tests and 5 h for the high-load tests or at failure, whichever occurred first. For the linerboard, we used creep loads of 22% and 30% of the compressive strength. The slightly higher percentages used for the corrugating medium caused failure after only a few cycles.

After test initiation, the specimen

4. Mean compressive strength of corrugating medium



5. Mean stiffness of corrugating medium



conditioning and data collection start immediately. Specimens undergo conditioning within the test chamber for six cycles of relative humidity before application of load. During this time, the control system compensates for specimen strain as a result of sorption to maintain zero load on the specimen. For the cyclic tests of relative humidity, we collected all data such as deformation, load, relative humidity, temperature, and time values at 50% and 90% RH both before and after application of load. For the tests of constant relative humidity, data collection intervals were the same as they were for the cyclic tests of relative humidity—5 min.

Figure 3 shows strain during a typical cyclic compressive creep test of relative humidity. Point A is the point of load application. The six preconditioning cycles are before point A. The maximum creep rate usually occurs during the primary portion of the creep test, although it may occur during the tertiary portion of the creep test. For this study, creep rate is the linear regression of six consecutive strain measurements at 50% RH. In Fig. 3, the test continued until failure.

Considine *et al* (*13*) found a strong correlation between minimum creep rate and duration of load. In the study reported here, because many tests terminated before failure, it was not possible to measure minimum creep rate or duration of load in all cases. Maximum creep rate does provide a measure of performance, however. Furthermore, in the end-use environment, most failures occur before a single component fails in compression. Thus, the creep testing of paperboard until failure has limited applications in the corrugated container industry.

The six cycles of relative humidity prior to load application measure hygroexpansive strain of the paperboard. Hygroexpansive strain is the strain from moisture sorption. Except for the release of papermaking-induced residual strains, this part of the test is nondestructive.

We performed compression tests at constant 50% and 90% RH to provide a comparative baseline. We preconditioned each specimen for 5 min at a relative humidity lower than the test relative humidity and then conditioned for 15 min at the test relative humidity before initiation of load. We then ramped the load at a rate of 263 N/m/s until failure occurred.

Results and discussion

This study had a small number of replications per creep test condition. Sufficient differentiation was evident in the compression tests. The result of the small number of replications is a lack of statistical differentiation between materials where differentiation may actually exist.

Analysis of variance (ANOVA) evaluated all test conditions. If the ANOVA showed that the materials were significantly different at the 5% level or less, a Tukey multiple comparison determined which materials were different from each other. In a few instances, the ANOVA showed that the materials were significantly different, but the Tukey test did not show a difference.

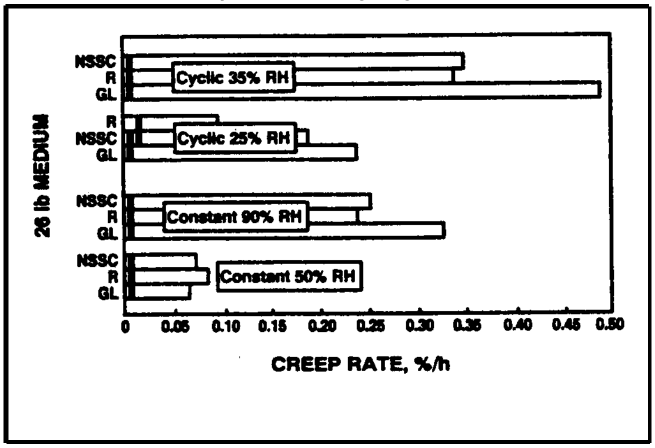
Depending on the property, either mean or median represented the data. If data have a normal distribution, the mean and median are identical. We used the median, for example, to represent the strain after 60 min under load. For some tests, the specimen failed before 60 min under load. In these cases, we used a large negative number, -10, to represent the strain. This procedure worked for all cases that had less than 50% failures. The use of the large negative number still allowed the calculation of the median.

Although we do not show it here, we also analyzed all data after normalization by the basis weight of the particular material The nonnormalized data did not affect the conclusions. Ranking stayed the same, although the level of significance did change in some cases.

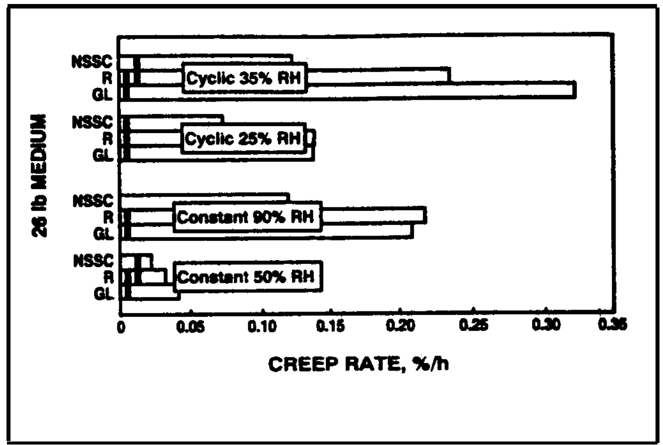
Corrugating medium

Figure 4 shows the means of compressive strengths. This figure contains heavy lines that connect values of two or more materials indicating that they are not statistically different from one another. A value with no

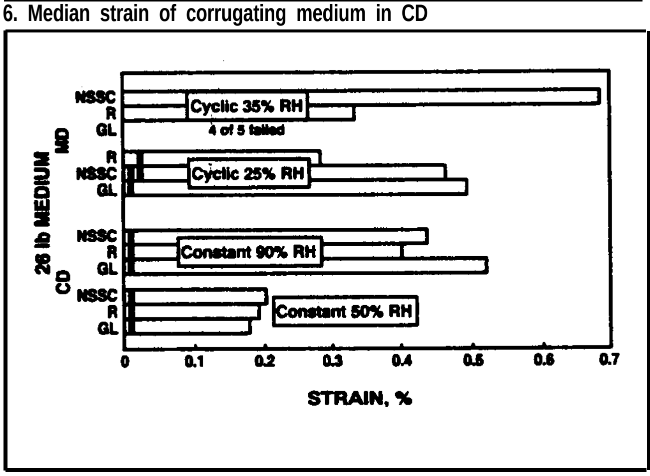
6. Mean maximum creep rate of corrugating medium in CD



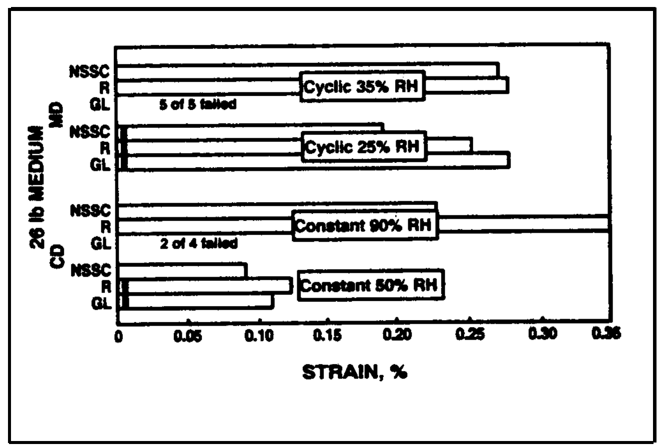
7. Mean maximum creep rate of corrugating medium in MD



6. Median strain of corrugating medium in CD



9. Median strain of corrugating medium in MD



lines connecting it to another is statistically different from all the others. The heavy lines in all the following figures have the same significance.

Some differentiation of materials is shown at 50% RH, but the corrugating medium had statistically similar strengths at 90% RH. Although there were no statistical differences, the NSSC corrugating medium was stronger in all cases.

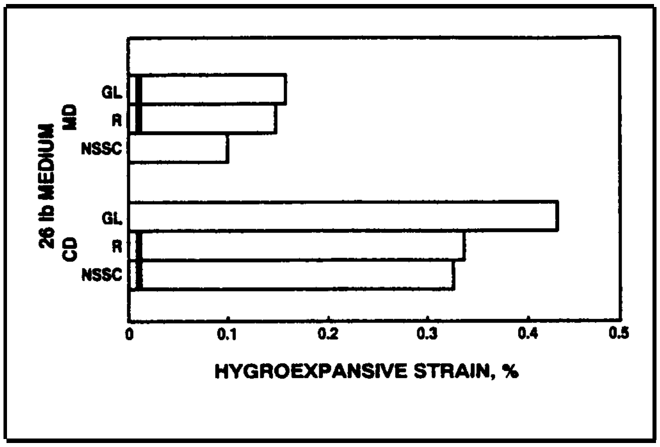
Figure 5 shows the mean corrugating medium stiffnesses. The stiffness values of the green-liquor (GL) and the recycled (R) corrugating medium were not different for any of the four test conditions. The NSSC corrugating medium had greater stiffness in the MD than did either of the other corrugating medium materials. All corrugating medium tests were statistically similar in the CD.

The corrugating medium compression tests indicated that all three corrugating medium materials had statistically similar mechanical properties. These results agree with those of Gunderson *et al* (*15*), which showed that, as expected, corrugating medium has lower compressive strength, greater compressive failure strain and lower stiffness at 90% RH than at 50% RH. The moisture content at 90% RH plasticizes the fibers and fiber-to-fiber bonds.

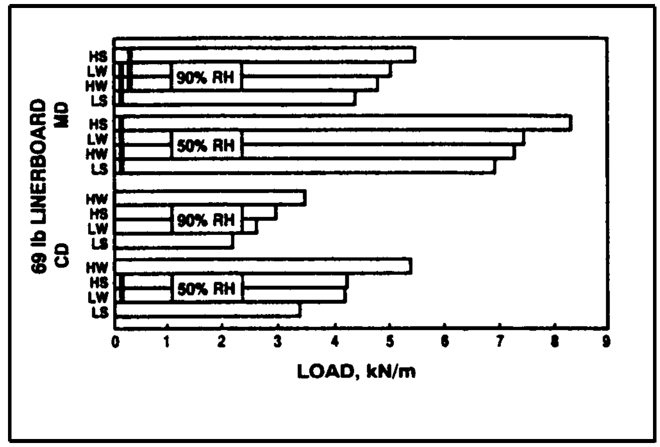
Figure 6 shows the mean maximum creep rates for the corrugating medium in the CD. The tests revealed few differences between the materials. Note that the creep tests at constant 90% RH showed slightly higher creep rates than did the cyclic tests of humidity at 25% load. Alternatively, the creep rates at constant 50% RH were very small. **Figure 7** shows the mean maximum creep rates for the corrugating medium in the MD. In all teat conditions, the NSSC corrugating medium had the lowest creep rates. In the MD, the R and the GL corrugating medium had statistically similar maximum creep rates.

Figure 8 shows the median strain at 60 min for the corrugating medium in the CD. Again there are few differences. Eighty percent of the GL corrugating medium specimens failed, however, when loaded to 35% of their compressive load in the cyclic environment. As previously mentioned (*13*), maximum failure strain does not appear to be an adequate prediction of failure. The NSSC corrugating medium had a large median strain after 60 min in the cyclic 35% condition because two of five specimens failed prior to 60 min.

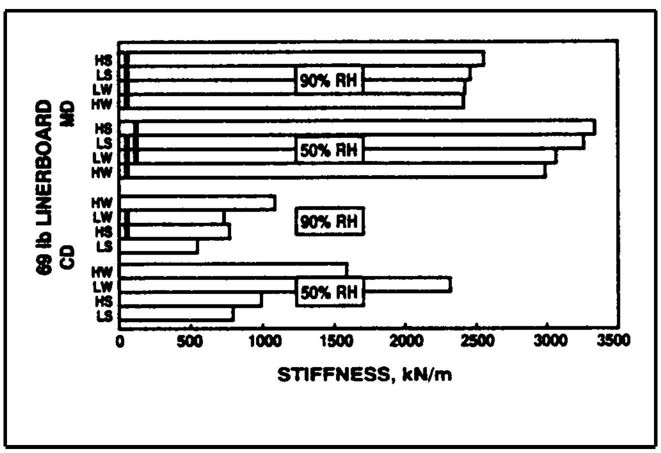
10. Mean hygroexpansive strain of corrugating medium



11. Mean compressive strength of 69-lb linerboard



12. Mean stiffness of 69-lb linerboard



13. Mean maximum creep rate of 69-lb linerboard in CD

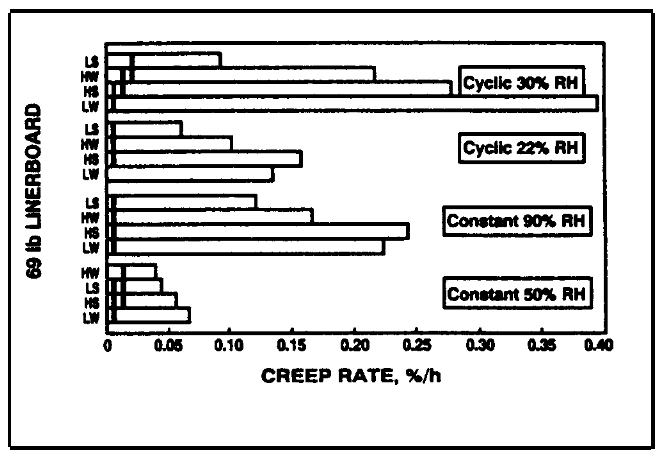


Figure 9 shows the median strain at 60 min for the corrugating medium in the MD. The GL corrugating medium was the only corrugating medium to have failures before 60 min under load. The R corrugating medium had one specimen fail before 60 min under load for the constant 90% RH condition. This is the reason for the large median strain value.

Figure 10 shows the mean hygroexpansive strain for the corrugating medium. For both MD and CD, the ranking of materials remained the same. The GL corrugating medium had the largest hygroexpansive strain, and the NSSC corrugating medium had the smallest hygroexpansive strain. The NSSC corrugating medium had the best creep performance, and the GL corrugating medium had the poorest creep performance. Therefore, hygroexpansive strain properly ranked the materials in order of performance-large hygroexpansive strain indicated poor creep performance and vice versa.

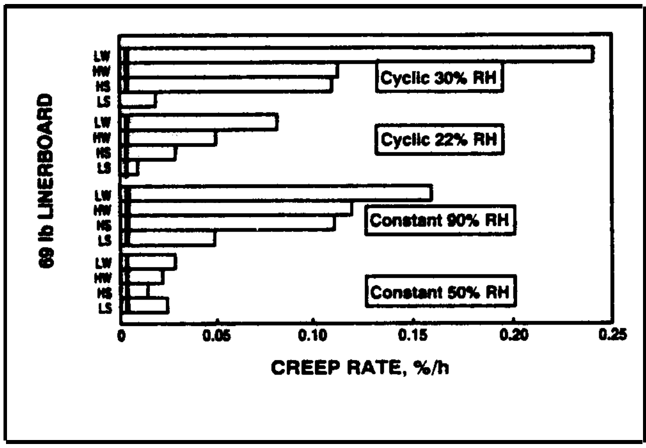
As a result of the large maximum creep rate and the large creep strain at 66 min of the GL corrugating medium, it was possible to conclude that this was the poorest performing corrugating medium in this study for both the CD and the MD. Individually, the properties of the GL corrugating medium may not have differed statistically from one of the other corrugating mediums. When taken together, however, the consistently poorer behavior of the GL material is evident. We did not reach this conclusion by considering only the compressive strength values at 50% RH of Fig. 4. The poor behavior of the GL corrugating medium in this study is not an indictment of the GL process, however.

69 lb linerboard

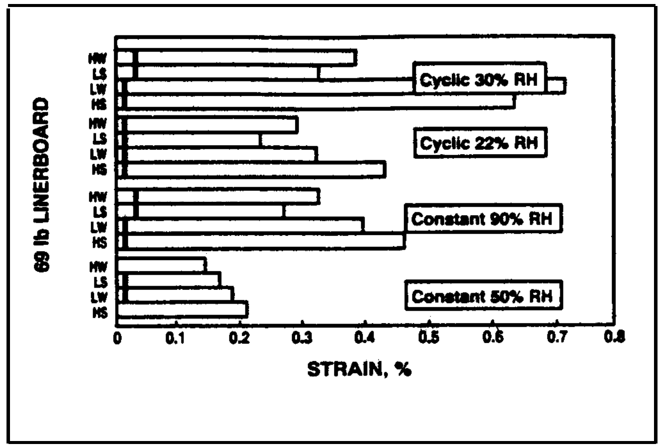
Figure 11 shows the mean compressive strength values of each of the 69 lb linerboard materials. The compressive strength values at 90% RH had more differentiation than did the compressive strength values at 50% RH. The LS linerboard had the lowest strength for all test conditions.

Figure 12 indicates the mean stiffness values for each 69-lb material. The stiffness values for both CD test conditions showed statistically significant differences between materials. The MD test conditions did not have large statistical differences. Component stiffness is an important property in the prediction of combined board behavior. With this in mind, note

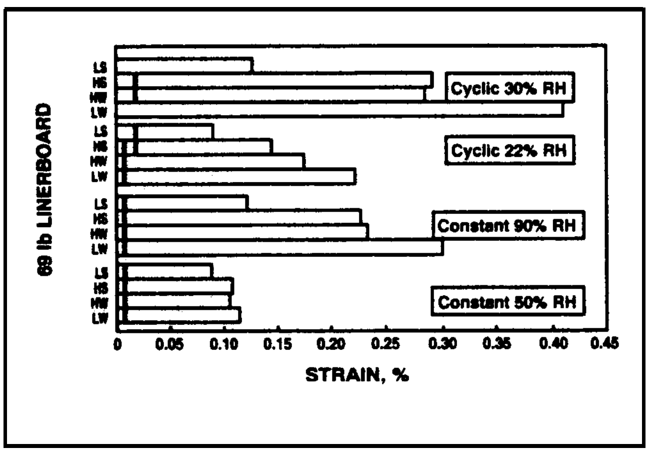
14. Mean maximum creep rate of 69-lb linerboard in MD



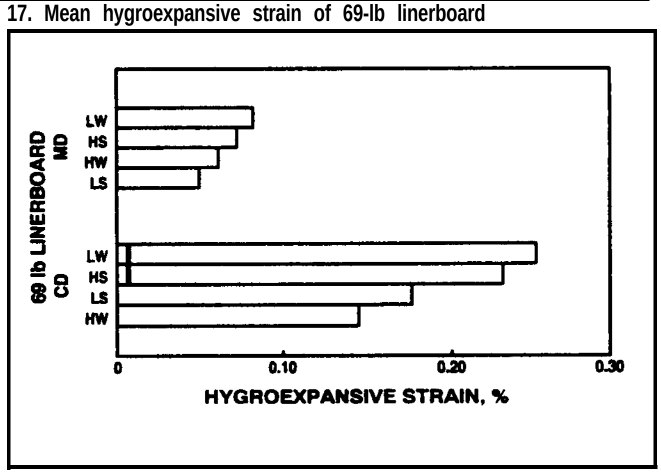
15. Median strain of 69-lb linerboard in CD



16. Median strain at 69-lb linerboard in MD



17. Mean hygroexpansive strain of 69-lb linerboard



that relative humidity affected the CD stiffness of the LW material. At 50% RH, LW had significantly greater stiffness than did the other materials. At 90% RH, LW ranked third. This example illustrates the problem with predicting behavior at different conditions of relative humidity. Relative humidity, i.e., moisture, does not affect all materials in the same manner and to the same degree.

Figure 13 provides the mean maximum creep rate for the 69-lb linerboards in the GD. Except for the condition of constant 50% RH, each test condition had the same material order. This ordering was not similar to the ordering of either of the compressive strength properties. Again, the order of severity of test conditions was (1) cyclic relative humidity, 30% load: (2) constant 90% RH, 30% load; (3) cyclic relative humidity, 22% load; and (4) constant 50% RH, 30% load.

Figure 14 shows the mean maximum creep rate for the 69-lb linerboard in the MD. There are few statistically significant differences. In three of the four test conditions, however, the LS material had the smallest maximum creep rate. The order of severity of test conditions was the same as for the CD.

Figure 15 shows the median strain at 60 min for the 69-lb linerboard in the CD. Except for the cyclic 22% test condition, there is some differentiation between materials. The LS material had the lowest values for each test condition except at constant 50% RH.

Figure 16 shows the median strain at 66 min for the 69-lb linerboard in the MD. The ordering for each test condition was the same. The order was the same as for the MD maximum creep rate indicated in Fig. 14. The lower creep rates for the LS material were not significant, but the amount of strain at 60 min was significant for both cyclic test conditions.

Figure 17 shows the mean hygroexpansive strains for the 69-lb linerboard. As with the corrugating medium, hygroexpansive strain appeared to predict the compressive creep behavior. The LS material had the best overall CD creep performance and the second lowest CD hygroexpansive strain. The LS material had the best overall MD creep performance and the lowest MD hygroexpansive strain. The LW material had the poorest overall creep performance in both the MD and CD and the largest hygroexpansive strain in both the MD and CD.

For the 69-lb linerboard, the LS material had the best overall compressive creep performance in both the MD and CD. This result is more significant in the MD, because the MD strength values for all the 69-lb linerboards were statistically the same. The creep loads were statistically the same.

Conclusions

This study provides a general overview of the compressive creep behavior of commercial paperboard corrugating components in four different moisture environments.

There was an additional normalization procedure which did not affect results. All creep loads were a percentage of the compressive strength of the particular material. If compressive creep performance relates directly to compressive strength, then all materials would have behaved in the same manner. For the linerboard, in no instance was the material performance ranking of the compressive creep tests the same as the material performance ranking by compressive strength.

Lack of replications per test condition hinders more definitive conclusions. Several important observations are possible, however:

- Statistical differences between the corrugating medium were small. The GL corrugating medium generally performed more poorly than did the other corrugating medium materials. Because there was only one type of corrugating medium from each production process, no generalizations are possible about the compressive creep performance behavior based on process type. This work did not include run-to-run machine variability. It is probably greater than the variability measured here. In this study, the recycled medium performed well which is contrary to the findings of Byrd (*3-5*).

- Statistical differences were small for the 69-lb linerboards. General trends developed, however. Perhaps one material was not statistically different from the others, but the ranking of materials remained the same for each test condition. **Table III** presents the general ranking for materials. The LS material had the best performance for both MD and CD. LW had the worst performance for both MD and CD.

III. General ranking for 69 lb materials

Direction	Ranking Best to Worst
CD	LS HW HS LW
MD	LS HS HW LW

- The severity of testing conditions was similar for all materials. The ranking of conditions from worst to best are as follows: cyclic RH at high creep load, constant 96% RH, cyclic relative humidity at low creep load, and constant 56% RH. This order is different than work reported by others. Other researchers indicated that creep strain under conditions of cyclic relative humidity was always greater than creep strain under constant high conditions of relative humidity. Most likely, this difference relates to the creep load.

- In most cases, the hygroexpansive strain was the best predictor of creep performance. This result is particularly important because hygroexpansive strain is a nondestructive test except for the release of papermaking-induced residual strains. For both material types, corrugating medium and 69-lb linerboard, the hygroexpansive strain had nearly the same order as the creep performance.

- The compressive strength of a material did not predict the compressive creep performance for any environmental condition examined in this study. It is unreasonable to assume that the failure and deformation mechanisms are the same for compressive strength and creep tests. Unlike the compressive strength tests, creep tests allow the material to deform and distribute the stresses in an optimal manner. In creep testing, the visco- elastic nature of the material becomes important.

These conclusions provide the preliminary work for the development of a test method or procedure that will evaluate the behavior of corrugated containers in varying moisture environments. TJ

Literature cited

1. Byrd, V. L., *Tappi* 55(2): 247(1972).
2. Byrd, V. L., *Tappi* 55(11): 1612(1972).
3. Byrd, V. L. and Koning, J. W. Jr., *Tappi* 61(6): 35(1978).
4. Byrd, V. L., *Tappi J.* 67(7): 86(1984).
5. Byrd, V. L., *Progress in Paper Physics–A Seminar on Design Criteria for Paper Performance*, STFI, Stockholm, p. 73 (1984).
6. Soremark, C. and Fellers, C., *TAPPI 1991 International Paper Physics Conference Proceedings*, TAPPI PRESS, Atlanta, p. 549.
7. Leake, C. H., *Tappi J.* 71(10): 71(1988).
8. Back, E. L., Salmen, L., and Richardson, G., *Svensk. Papperstid.* 86(6): R61(1983).
9. Back, E. L., Salmen, L., and Richardson, G., *J. Pulp Paper Sci.* 11(1): J8(1985).
10. Berger, B. J. and Habeger, C. C., *J. Pulp Paper Sci.* 15(5): J160(1989).
11. Gunderson, D. E., *J. Pulp Paper Sci.* 17(2): J53(1991).
12. Gunderson, D. E. and Tobey, W. E., in *Materials Interactions relevant to the Pulp, Paper and Wood Industries* (D.F. Caufield, J.D. Passaretti, and S.F. Sobczynski, Eds.), Materials Research Society, Pittsburgh, 1990, p. 213.
13. Considine, J. M., Gunderson, D. E., Thelin, P., *et al.*, *Tappi J.* 72(11): 131(1989).
14. Considine, J. M. and Gunderson, D. E., *Exp. Tech.* 11(9): 18(1987).
15. Gunderson, D. E., Considine, J. M., and Scott, C. T., *J. Pulp Paper Sci.* 14(2): J37(1988).

The Containerboard and Kraft Paper Group of the American Forest and Paper Association pardally funded this work The authors gratefully acknowledge their support and guidance.

Received for review Feb. 21, 1993.

Accepted May 12, 1993.

Printed on recycled paper